

Laser ablation loading of a surface-electrode ion trap

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We demonstrate loading by laser ablation of $^{88}\text{Sr}^+$ ions into a mm-scale surface-electrode ion trap. The laser used for ablation is a pulsed, frequency-tripled Nd:YAG with pulse energies of 1-10 mJ and durations of 3-5 ns. An additional laser is not required to photoionize the ablated material. The efficiency and lifetime of several candidate materials for the laser ablation target are characterized by measuring the trapped ion fluorescence signal for a number of consecutive loads. Additionally, laser ablation is used to load traps with a trap depth (40 meV) below where electron impact ionization loading is typically successful ($\gtrsim 500$ meV).

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Trapped ions have been shown to be one of the most promising platforms for large-scale quantum information processing (QIP). Recently, development has begun on miniaturized and scalable ion traps [1, 2, 3, 4, 5]. While these efforts have met with some success, current designs suffer from technical challenges such as a relatively small trap depth and greater sensitivity to stray electric fields compared with the traps used in previous QIP experiments. Both of these problems can interfere with loading ions. For example, the loading of a surface-electrode printed circuit board ion trap with electron impact ionization presented in [6] was hindered by stray charges until buffer gas cooling was implemented and micromotion compensation performed. Photoionization has been used to load shallow ion traps [1, 2, 3], but it requires additional frequency stabilized lasers which are not readily available for every ion species. A new and elegant method in which atoms are photoionized directly from a MOT has been shown to efficiently load ions at a few mK [7], but the laser requirements are even more demanding than for standard photoionization loading.

Laser ablation of a solid target has been used to load ion traps as early as 1981 [8, 9]. Ablation is a process in which a high-intensity laser strikes a surface, causing the rapid ejection of material that includes neutral atoms, ions,

molecules, and electrons [10]. With other methods of ion loading, the neutral atoms are ionized inside the trapping region. This, however, is not the case with ablation. It was shown in [11] that the electrons from the ablation plume reach the ion trap first and short the trap electrodes for an amount of time on the order of 10 μs , and the ions from the ablation plume which are passing through the trapping region when the trap voltages recover may be captured. A recent paper demonstrated an alternative way to load ion traps with ablation which uses photoionization to ionize the neutral atoms in the ablation plume as they pass through the trap region [12].

Laser ablation loading is potentially advantageous for QIP for two reasons. First, it is very fast: ions can be loaded with a single laser pulse in much less than one second. And second, because the heat load is negligible small ablation targets could be integrated with a multi-zone trap for localized loading. Thus far, however, no work has been done to determine whether ablation is a viable method for loading the miniaturized and scalable ion trap designs proposed for large-scale QIP.

This paper examines ablation loading of a shallow, surface-electrode ion trap similar to the designs proposed for large-scale QIP. We characterize several candidate materials for the ablation target to determine which materials are

the most efficient and last the longest for loading $^{88}\text{Sr}^+$, then proceed to find the minimum trap depth at which laser ablation loading is possible in this trap.

The ion trap used for this work is a printed circuit board surface-electrode Paul trap [6, 7, 13, 14] shown in Fig. 1. The trap is typically operated with 200-600 V rf amplitude at 8 MHz. The trap is mounted in a ceramic pin grid array (CPGA) chip carrier, which is plugged into a custom built ultra-high vacuum (UHV) compatible CPGA socket [2]. The socket is installed in a vacuum chamber evacuated to 2×10^{-9} torr. A schematic of the experimental setup is shown in Fig. 2.

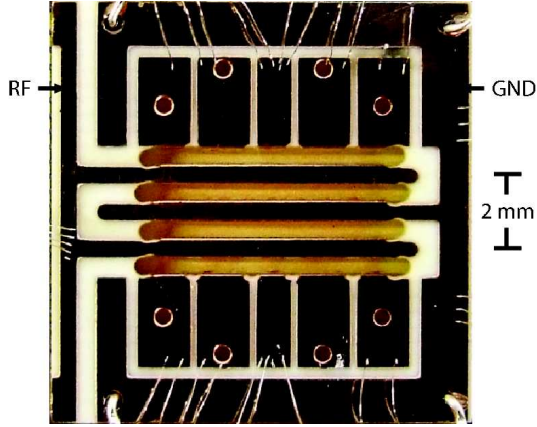


FIG. 1: (color online) The surface-electrode ion trap used for testing ablation loading. The RF electrodes are spaced by 2 mm, leading to an ion height above the trap of 0.8 mm. The long center electrode is held at rf ground, but may have a dc offset applied to it. The segmented electrodes on the sides carry dc potentials for confinement along the long axis of the trap, as well as elimination of stray electric fields.

We detect $^{88}\text{Sr}^+$ ions using laser-induced fluorescence on the 422 nm $5S_{1/2} \rightarrow 5P_{1/2}$ transition, with a 1092 nm repumper beam addressing the $4D_{3/2} \rightarrow 5P_{1/2}$ transition to prevent electron shelving in the metastable $4D_{3/2}$ state. Fluorescence is observed using either a photon counting photomultiplier tube (PMT) or an electron-multiplying CCD camera.

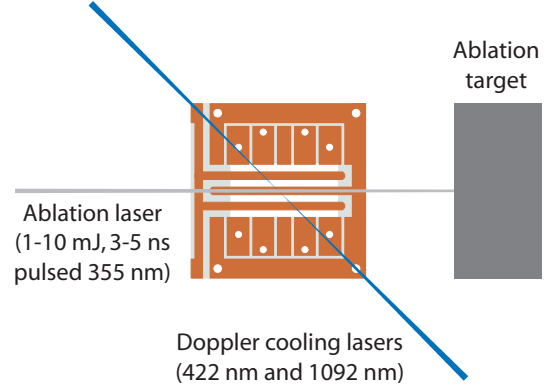


FIG. 2: (color online) A diagram of the setup showing the position and orientation of the ablation target relative to the ion trap. The surface of the ablation target is approximately 25 mm from the trap center and is orthogonal to the direction to the ion trap. Not to scale.

The laser used for ablation is a pulsed, frequency-tripled Continuum Minilite Nd:YAG laser at 355 nm. No additional photoionization lasers are used. We load ions using a single laser pulse of energy 1-10 mJ and duration 3-5 ns. Ion numbers ranging from one to a few hundred are obtained with a single pulse.

The efficiency of laser ablation loading is strongly dependent on the ablation target material. We studied several target materials by measuring the trapped ion signal as a function of the number of ablation laser pulses fired on a single spot of the target. Each ablation laser pulse knocks the ions from the previous pulse out of the trap, so the trapped ion signal is roughly proportional to the number of ions loaded by a single ablation pulse. This measurement provides a benchmark of the loading efficiency and the durability of the target.

The target materials studied here are Sr (99% pure random pieces from Sigma-Aldrich), Sr/Al alloy (10% Sr, 90% Al by mass from KB Alloys), single crystal SrTiO_3 ($\langle 100 \rangle$ crystal orientation from Sigma-Aldrich), and SrTiO_3 powder in an epoxy resin (5 μm SrTiO_3 powder from Sigma-Aldrich mixed with Loctite 5 minute epoxy). In

Fig. 3 we plot experimental results for each of these targets. It is clear that from a standpoint of durability and consistency that the SrTiO_3 crystal is the best choice of target material for loading $^{88}\text{Sr}^+$. We are not concerned about the relatively lower efficiency of SrTiO_3 because we are primarily interested in loading small numbers of ions.

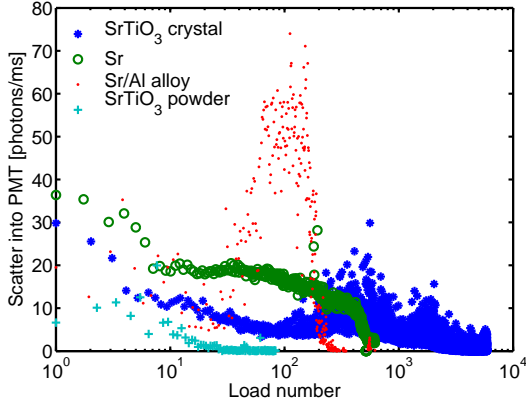


FIG. 3: (color online) A plot of the trapped ion signal as a function of the number of ablation pulses for several different ablation targets. Each point represents the signal due to a single ablation pulse of energy 8 mJ. For this experiment, the ablation laser was focused to a spot size of $300\ \mu\text{m}$. For reference, a single ion scatters roughly 2.5 photons/ms into the PMT in this setup.

We also measured the dependence of the trapped ion signal on the trap depth. In this experiment, ions were loaded into the trap at a series of decreasing rf voltages which correspond to decreasing trap depths. We calculate the trap depth based on the time independent secular potential using a boundary element electrostatics solver [14, 15], and verify that the secular potential is accurate by checking that it gives secular frequencies which match the experiment at each rf voltage. The trapped ion signal for each trap depth is plotted in Fig. 4. The ablation laser pulse energy of 1.1 mJ and spot size of $680\ \mu\text{m}$ were chosen to maximize the ion signal at low trap depth. We found that the lowest trap depth at which we could load using

laser ablation is 40 meV. In contrast, the same experiment using electron impact ionization of a thermal atomic beam loaded a minimum trap depth of 470 meV.

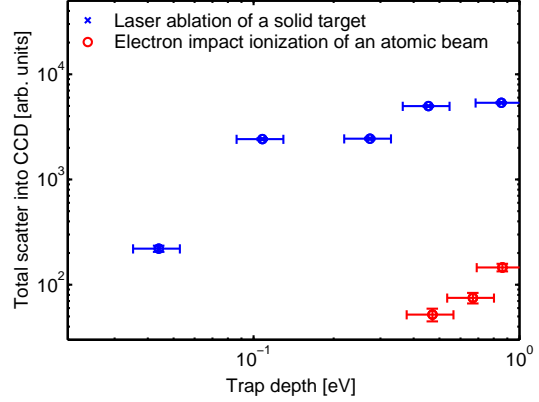


FIG. 4: (color online) A plot of the trapped ion signal as a function of the computed trap depth for both ablation and electron impact ionization loading. An ablation pulse energy of 1.1 mJ was used with a spot size of $680\ \mu\text{m}$. Each point is the ion signal obtained either from a single pulse of the ablation laser or from loading using electron impact ionization until the ion signal stops increasing.

The 40 meV trap depth loaded here with ablation is similar to the shallowest trap depths loaded with photoionization of a thermal atomic beam [2]. Additional criteria to consider when selecting a loading method for QIP include isotope selectivity and matter deposited onto the trap electrodes. Matter deposited onto the trap electrodes is suspected to increase the heating rate of the motional state of trapped ions [16, 17]. Photoionization loading is isotope selective [18, 19] and deposits much less matter onto the trap electrodes than electron impact ionization loading [20]. The isotope selectivity of ablation loading is similar to that of electron impact ionization loading when loading the ions in the ablation plume as in this work. It is possible, however, to implement ablation loading in an isotope selective manner by photoionizing the neutral atoms in the ablation plume [12]. We have measured the ion heating rates

in cryogenic ion traps loaded with laser ablation and found them to be quite low [21], which suggests that ablation does not deposit much matter onto the trap electrodes.

In conclusion, we have used laser ablation of a solid target to load a surface-electrode ion trap. Several candidate materials for the ablation target are characterized, and single crystal SrTiO₃ is found to give the best performance for loading

⁸⁸Sr⁺. Laser ablation is demonstrated to work for loading surface-electrode ion traps at trap depths as low as 40 meV. When combined with the isotope selectivity and cleanliness demonstrated elsewhere, these results suggest that laser ablation is a viable loading method for large-scale ion trap QIP.

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